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Environmental Interactions of the Space Station Freedom Electric Power System

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ABSTRACT

The Space Station Freedom will be operating in the Low Earth Orbit (LEO) environment. Such operation results in different potential interactions with the Space Station systems including the Electric Power System (EPS). These potential interactions result in environmental effects which include neutral species effects such as atomic oxygen erosion, effects of micrometeoroid and orbital debris impacts, plasma effects, ionizing radiation effects, and induced contamination degradation effects. ***The purpose of this paper is to briefly describe the EPS design and its interactions with the LEO environment and to discuss the results of analyses and testing programs planned and performed thus far to resolve the environmental concerns related to the EPS and its function in the LEO environment.***

Keywords: Environmental Interactions, Space Station Electric Power System, Atomic Oxygen, Plasma, Ionizing Radiation, Meteoroid and Orbital Debris, Induced Contamination.

1. SPACE STATION FREEDOM ELECTRIC POWER SYSTEM DESCRIPTION

The Electric Power System of the Permanently Manned Configuration (PMC) of the restructured Space Station Freedom Program consists of three Photovoltaic Power Modules and the Power Management And Distribution (PMAD) dc system. Each Photovoltaic (PV) Power Module consists of two solar arrays for power generation, NiH_2 batteries for energy storage, a PV module thermal control system which comprises cold plates and a radiator for heat acquisition and dissipation and for thermal conditioning of the batteries and PMAD equipment, and an integrated equipment assembly which serves as the structure for the batteries and PMAD Orbital Replacement Units (ORUs), (Ref. 1). Figure 1 shows the Space Station Man Tended Configuration (MTC) while Figure 2 displays the Permanently Manned Configuration (PMC).

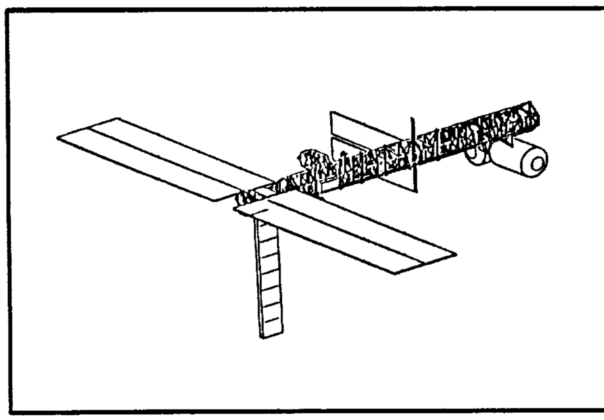


Figure 1. Schematic of the Post Restructuring Man Tended Capability Configuration (MTC)

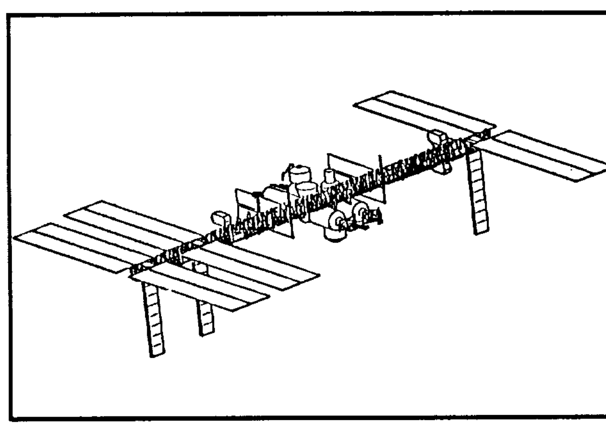


Figure 2. Schematic of the Post Restructuring Permanently Manned Capability (PMC) Configuration

2. ATOMIC OXYGEN EFFECTS ON EPS MATERIALS

2.1 Atomic Oxygen Environment

Atomic oxygen (AO) is the most abundant species in the LEO environment. Being a highly reactive species, atomic oxygen reacts differently depending on the nature of materials. Metals tend to develop an oxide on the surface after reacting with neutral atomic oxygen whereas polymers tend to lose mass and undergo a change in surface morphology. Atomic Oxygen effects on metallic and nonmetallic materials were detected during the Space Shuttle Missions (Ref. 2). The Evaluation of Oxygen Interaction with Materials (EOIM I and II) flight experiment were designed and flown for the purpose of evaluation of reaction rate constants and reaction efficiencies.

Table 1 shows the reaction efficiencies of different materials from measurements of lost mass and calculation of expected fluence during the Space Shuttle missions.

Material	Reaction Efficiency (cm^3/atom)
Kapton®	3.0 10^{-24}
Mylar	3.4 10^{-24}
Tedlar	3.2 10^{-24}
Polyethylene	3.7 10^{-24}
Polymethylmethacrylate	3.1 10^{-24}
Polyimide	3.3 10^{-24}
Polysulfone	2.4 10^{-24}
1034C Epoxy	2.1 10^{-24}
5208/T300 Epoxy	2.6 10^{-24}
Teflon TFE	$<.05 10^{-24}$
Teflon FEP	$<.05 10^{-24}$

Table 1. Reactivities of some Composites, Polymers, and Organic Films as Measured in Space

2.2 Atomic Oxygen Effects

2.2.1 Design Solution: Due to their high reactivities with atomic oxygen, polymers and composites on the space station will be protected from atomic oxygen threats. The solar array substrate for instance which is made of Polyimide Kapton®[1] presented a major survivability concern in the neutral atomic oxygen environment. Several options were considered for protection of the solar array substrate. Protection by thin film protective coatings was considered optimal because thin films tend to preserve the desirable optical properties of Kapton® such as infrared transmission which has a direct effect on the solar cell operating temperature, and tend to have a low impact on the overall mass of the solar array. Silicon oxide thin films (1000 to 1300 A) were developed by ion beam sputter deposition at LeRC, tested for atomic oxygen resistance, flexibility and internal stresses and implemented for the protection of the array substrate (Ref. 3). The baseline design of the solar array panels currently calls for silicon oxide thin film protection against atomic oxygen threats.

2.2.2 Directionality Effects: The Space Station will fly variable altitude flight path such that the density (and therefore the corresponding drag) experienced by the SSF surfaces is nearly constant. This results in an atomic oxygen flux on the EPS surfaces that is nearly constant in time and depends on the orientation of the surface with respect to the local vertical–local horizontal coordinate system. Surfaces with the normal parallel to the velocity vector are known as ram surfaces and tend to receive the maximum AO flux. Solar pointing surfaces (such as the solar array surface pointing at the sun) with normal parallel to the sun vector tend to receive less AO flux than antisolar surfaces due to the high density region residing at 40 degrees from the solar noon. Edge to sun surfaces such as the radiator surfaces tend to receive AO flux that is nearly of the same level as the solar and antisolar surfaces. Figure 3 shows the orientation of different surfaces and Table 2 shows the flux incident on different surfaces. Moreover, Table 3 shows the assumptions made in the flux calculation. The AO flux calculated and shown in Table 2 below can be used to calculate the surface recession of unprotected polymers of specific thickness by multiplying the flux by the mission time and the reaction efficiency.

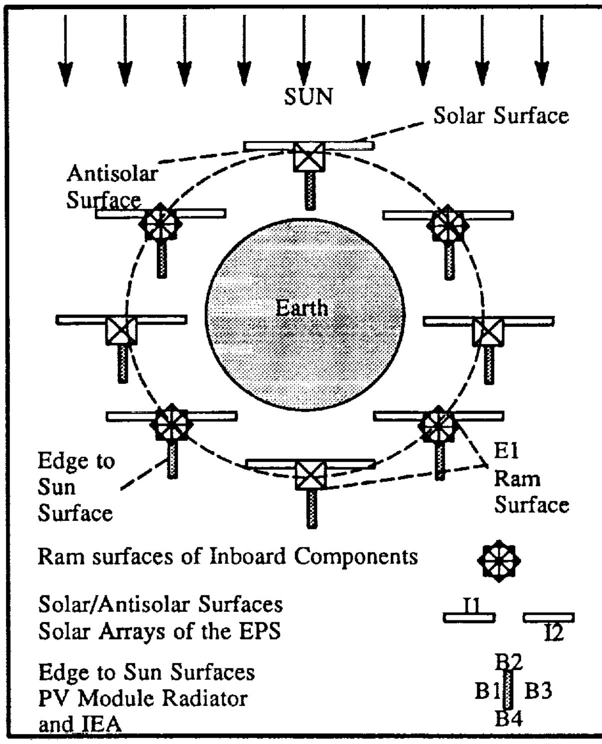


Figure 3. Schematic of EPS Component Surfaces and their Rotations Through One Orbit

Component	Surface Orientation	Flux AO/cm^2–s
Solar Array	Solar Surface	3.5 10^{13}
	Antisolar //	4.4 10^{13}
IEA and PV Radiator	B1	5.0 10^{13}
	B2	3.9 10^{13}
	B3	3.8 10^{13}
	B4	4.9 10^{13}
Ram Surfaces of Inboard Components	E1	1.4 10^{14}

Table 2. Results of Predicted Atomic Oxygen Flux Based on Conditions of Table 3.

Variable/Parameter	Assumption
Altitude	411 km
Geomagnetic Index (Ap)	35
$F_{10.7}$	230
Date	December 17–Mean
Local Time	Diurnal Mean 9:a.m
Latitude	Latitude Mean 0 deg
Longitude	0 deg.

Table 3. Assumptions of parameters used in the AO Flux Calculations

Although surface recession is a measure of degradation for unprotected polymers, it is not adequate for SiOx coated Kapton because silicon oxide is inert to the atomic oxygen environment. Degradation of coated underlying Kapton occurs through coating and manufacturing induced defects. Such degradation has been studied and results show that even with the pinhole defects induced in the coating from the deposition

[1] Registered Trademark of Dupont de Nemours and Co., Inc.

process, the effective reaction efficiency is two to three orders of magnitude lower than unprotected Kapton which makes the SiOx coating a viable protection to the Kapton used for the solar array substrate (Ref. 3).

3. METEOROID AND ORBITAL DEBRIS EFFECTS

Meteoroid and orbital debris impacts induce physical damage on the impacted surfaces due to the high impact velocities. Spalling of and penetration through surfaces are two of the familiar physical effects created by hypervelocity impacts. Such failure mechanisms tend to have different effects on the EPS components and subsystems which will be discussed following the Meteoroid and Orbital Debris environment brief descriptions

3.1 Meteoroid Environment Description

The meteoroid environment encompasses particles originating from natural sources such as comets and asteroids. Two types of meteoroid fluxes have been identified. Streams are periods of high flux created from the meteoroid resulting from their parent body whereas sporadic meteoroid fluxes are those that occur randomly with no apparent pattern. The average total meteoroid flux is comprised of the average sporadic and annual average meteoroid streams. Meteoroids are omnidirectional with respect to Earth, move with an average velocity of approximately 17 km/sec and have density of approximately 0.5 g/cm^3 for particles of masses above .01 g. The average annual flux of meteoroid is given by relations which relate the flux with the particle mass. The flux is then multiplied by factors such as the focusing and shielding factors that account for the earth shielding and its gravitational effects (Ref. 5).

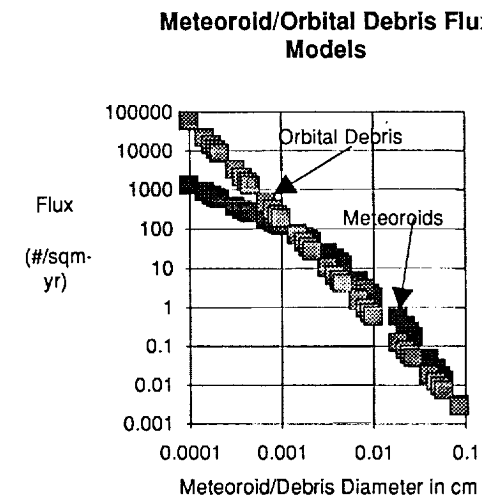
3.2 Orbital Debris Environment Description

Compared to the natural meteoroid environment represented at any instant of time by 200 kg of mass within the 2000 km altitude from the Earth surface, there exist 1.5 to 3 million kg of man made orbiting objects most of which are in the high inclination orbits. In addition to the main objects that are being tracked by the US Space Command, there exists 20,000 kg of satellite fragmentations. For the smaller diameter objects, there exists in LEO approximately 1000 kg of orbital debris of diameter less than 1 cm and about 300 kg of debris less than 1 mm (Ref. 5).

Calculation of the orbital debris flux on a surface in a particular orbit requires knowledge of the date of beginning of mission, the solar activity $F_{10.7}$ parameters predicted for the mission, and the orbital parameters such as the altitude and the inclination. Figure 4 shows the orbital debris and meteoroid fluxes where the orbital debris environment is calculated for an altitude of 400 km, $F_{10.7}$=70 and an inclination of 28.5 degrees (Ref. 5).

3.3 M/OD Impacts on the EPS Hardware

Analyses of the M/OD threats consist of predicting the damage induced by hypervelocity impacts. Moreover, given a failure criteria, one can calculate the probability of occurrence of such a failure and its effect on the system. In order to evaluate the probability of occurrence or non–occurrence of a failure, the number of damaging particles based on the failure criteria



Altitude	400 km
$F_{10.7}$	70
Year	1990

Figure 4. Orbital Debris and Meteoroid Flux as a Function of Particle Diameter

must first be calculated. If we assume for instance that the failure criteria of an Orbital Replacement Unit (ORU) is a penetration through the unit wall, then the number of penetrating particles is calculated. The number of penetrating particles on a surface, N, is calculated given the surface relative direction with respect to the local vertical–local horizontal set of coordinates, its orbital parameters such as altitude and inclination, flux and penetration models applicable to the surface material and geometrical characteristics.

3.3.1 M/OD Effects on ORUs: Hypervelocity impacts of Meteoroid or Orbital Debris particles on the ORU boxes could cause penetration through the ORU box wall and partial or complete damage to electrical components inside the ORU. The number of penetrating particles can be computed by integrating over the possible range of angles that the surface normal will face if the surface changes orientation with respect to the local vertical–local horizontal coordinate system, by also integrating over the possible velocities and time if the flux model is time dependent which is the case with respect to the orbital debris (Ref. 4). From the calculation of N the probability of no penetration can be calculated using Poisson cumulative probability distribution.

Calculation of the total number of penetrations can be used to optimize the ORU box wall thickness based on the minimum of the life cycle cost–ORU box wall thickness curve. The life cycle cost of a particular ORU can be calculated from the probability of no penetration which can be translated into a mean replacement interval for a specific box wall thickness. The thickness can be varied and the same calculation can be performed until a minimum life cycle cost is reached.

3.3.2 M/OD Effects on Solar Array Assembly: Impacts of Meteoroids and Orbital Debris on the solar array assembly result in degradation of the solar array performance i.e. degradation in delivered power. Analysis of these impacts on the array yields a degradation factor due to the Meteoroid and Orbital Debris environment. Contributors to the degradation in delivered power are damaged solar cell area due to impacts, failure of solar cell strings, interstrings connecting circuits and solar cell circuits (two panels in series=one circuit). Preliminary assessment of the M/OD effects on the solar array resulted in a degradation factor of approximately 3.5% over 15 years which was based on the recent revision of the M/OD environmental models evaluated at 215 n.m. altitude and $F_{10.7}=70$.

4. IONOSPHERIC PLASMA EFFECTS

4.1 Plasma-Spacecraft Interactions

The Low Earth Orbit ionospheric environment consists of a conductive plasma. During the sunlight portion of the orbit, the spacecraft solar arrays act as a voltage source which result in a voltage distribution induced on the spacecraft surfaces, which in turn allows conductive surfaces to collect currents from the plasma. Moreover, since electrons and ions in the plasma differ significantly in mass, this makes electrons move faster than ions, which in turn makes electrons easy to collect whereas ions are difficult to collect due to their lower mobility. Then, a small portion of the spacecraft will be positive with respect to the plasma potential defined as zero volts, and be collecting electrons, and the rest will be negative relative to the plasma potential and be collecting ions. Depending on the grounding of the solar arrays to the spacecraft structure, the spacecraft could be near the zero potential for grounding the positive end of the array to the structure, or could be significantly negative from the plasma potential for grounding the negative end of the array to the structure. Figure 5 is a schematic of these concepts (Ref. 6).

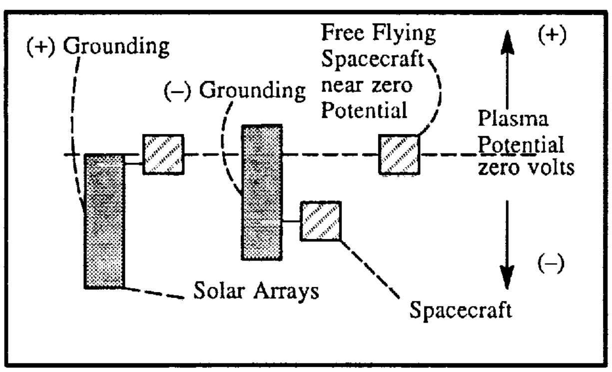


Figure 5. Floating of a Spacecraft with High Voltage Solar Arrays in the Space Plasma

4.2 Space Station-EPS Plasma Concerns

Historically, solar array operating voltage on typical spacecrafts is lower than the 160 V of the Space Station. Therefore grounding of the solar arrays has not been a plasma issue for spacecrafts. With current grounding design of the EPS and the SSF structure which calls for grounding the reference point to the negative side of the array, several possible plasma issues have been identified and are being studied by the plasma community under the auspices of the Electrical Grounding Tiger Team (Ref. 7). These issues are summarized as follows:

4.2.1 Structure Potential: With negative grounding,the structure potential will be different from the plasma potential. Some estimates which assume a conductive area of 200 m^2 show that the ground reference and the structure could float between 130 to 150 volts below the plasma potential. Proposed mitigation solutions to the potential difference such as reducing the electron collection area and effectiveness, increasing the ion collection area and using active charge control system such as plasma contactors are currently under consideration.

4.2.2 Sputtering/Contamination Effects: Although the issue of erosion by 5 eV neutral atomic oxygen has been known since the early flight missions, erosion by ionic oxygen accelerated to 100 eV presents new concerns. Sputtering is expected to occur on the structure and the solar array since most of the structure and the solar array float negatively with respect to the plasma. Sputtering of the structure is expected to occur through the pinholes and meteoroid and debris induced craters in the aluminum oxide anodize layer which in turn allow the plasma to be collected at approximately 140 eV with an enhancement in the sputtering rate due to ion focusing. Sputtering presents another contamination source to the space station and the power system. Sputtering products are a concern since deposition from these products could degrade the optical performance of the sensitive surfaces like other contamination effects. Sputtering effects are being analyzed currently to assess the impact of such effects on the performance of the EPS components.

4.2.3 Arcing: Arcing threshold for the solar array was studied extensively under the Plasma Interaction Test (PIT) Program initiated at LeRC to investigate the arcing and current collection phenomena on the Space Station solar arrays in the plasma environment. The test article in this test was one solar array circuit consisting of two solar array panels in series with active solar cells of the Space Station design. Measurement of the arcing threshold indicated that solar array arcing threshold is between –210 and –245 V relative to the plasma potential (Ref. 8). Arcing potential threshold of the structure is still an unknown and must be investigated thoroughly since arcing can be a significant source of Electromagnetic Interference due to the current transients produced during an arc.

4.2.4 Current Collection: The aforementioned PIT program investigated current collection on the solar array panels as function of the plasma density. The results showed that as the plasma density increases, electron and ion current collection increases. Figure 6 show these results. The plasma current collection measured in this test was negligible compared to the currents actively generated by the solar panels (Ref. 8).

4.2.5 Pyrolization and Dielectric Breakdown: Material degradation and disintegration due to current collection is a concern. High electron current collection on the panel substrate, Kapton, could cause local heating such that the Kapton may undergo pyrolization which causes local permanent damage to the panel substrate. Moreover dielectric breakdown of the anodized layer is a major issue since the dielectric materials will have to withstand the potential difference of approximately 160 volts. Dielectric breakdown of the anodize aluminum will most likely occur unless the thickness, the material, and the process are selected such that the coating can withstand the aforementioned potential difference (Ref. 6).

5. IONIZING RADIATION EFFECTS

5.1 Ionizing Radiation (IR) Environment

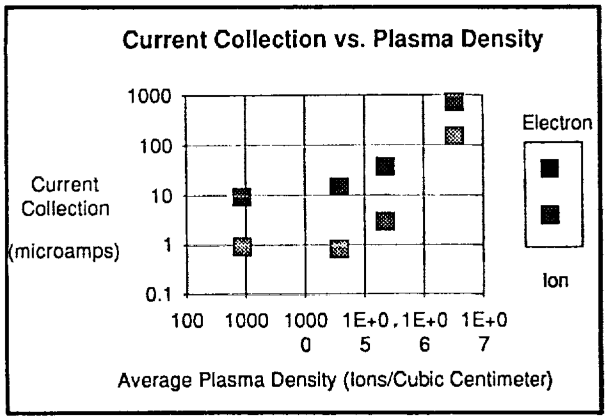


Figure 6. Results of the Parasitic Current Collection Tests

Because of their significant energy and penetrating capability, the ionizing radiation or penetrating charged particles introduce a major challenge to the design of the EPS components such as electronic boxes and the solar cells that are potentially affected by such an environment. The ionizing radiation environment is divided into two groups, magnetospheric particles and cosmic rays. Magnetospheric particles (trapped radiation) are accelerated by processes inside the magnetosphere. The trapped radiation energy ranges from KeV for electrons to MeV for protons and tend to populate the radiation belts (Van Allen Belts) which follow the geomagnetic field lines. On the other hand, cosmic rays which consist of electrons, protons and nuclei from all elements exist in interplanetary space and tend to enter the magnetosphere if their energy level is high enough to overcome and not be deflected by the geomagnetic field strength. For Low Earth orbits with low inclination (like the Space Station orbit), the geomagnetic field tends to deflect a portion of the cosmic rays of certain energy and mass. Cosmic rays are divided in two groups, galactic which are thought to have originated outside the solar system, and solar which originate from the sun occasionally during solar flares. The environment is defined by using AP8MIN and AP8MAX for trapped proton at solar minimum and maximum respectively, and AE8MIN and AE8MAX for trapped electron during solar minimum and maximum respectively. Galactic and solar cosmic rays environment is defined by a set of empirical equations given in SSP 30425 (Ref. 5).

5.2 Impact of Ionizing Radiation On EPS

The effects of ionizing radiation on the EPS hardware are primarily represented by the IR total dose effect on electronics and solar cells, and single event upset (SEU), and latchup occurring on electronics.

5.2.1 Description: The total dose effects result in changes in the electrical properties of semiconductors. Such change is due to the radiation induced changes in the oxide layer such as depletion of electrons and creation of traps in the oxide–semiconductor layers. The SEUs result from heavy ions passing through sensitive volumes of microcircuits. Moreover, fragmentation products from proton–induced nuclear reactions with nuclei can further cause SEUs. Such effects include loss of bits in memories, registers and microprocessors which are the direct results of induced ionization in the device. Latchup is the direct result of charged particles penetration in a device that remains in a given state after an event. Degradation of performance of solar cells is the result of electrons and protons penetrating the silicon lattice and causing ionization.

5.2.2 Analysis and Results: Analysis of the IR effects consists of defining the environment from which different calculations can be made. Details of these calculations are reported in Reference 4. Results of the total dose calculation show that the design criteria total dose of 10 Krad is adequate for EPS components having design life less than 20 years. SEU and latchup rates calculation result in identification of SEU hardened devices which are reported in Reference 4. Solar cell performance degradation calculation which involves converting the electron and proton fluence to equivalent 1 MeV electron and 10 MeV proton fluxes from which the degradation in solar cell characteristics can be computed, results in a degradation of 9.57% over 15 years for the worst case SSF Ionizing Radiation environment (Ref. 4).

6. INDUCED CONTAMINATION EFFECTS

6.1 Description of the Induced Contamination Environment and Effects

The induced contamination environment also affects the performance of the solar arrays and other sensitive surfaces of the EPS such as the Photovoltaic Power Module Radiator. Induced contamination environment is the result of sources releasing contaminants to the LEO environment. Because of the molecular collision and interaction that take place between the ambient environment and the contamination flux released from the surface as an outgassing product or from sources such as vents, thrusters, or leaks, a portion of the contaminant will return to the surface as return flux which results in contaminant deposition. Return flux from contamination increases the local density of the neutral environment. Such increase in the density results in an increase in the molecular column density which affects the deep space observation opportunities. As far as the EPS sensitive surfaces are concerned, the contamination deposition on the solar cells degrades the transmission coefficient and could raise the operating temperature of the cell due to an increase in the solar absorptance. The decrease in the transmission coefficient and increase in solar cell operating temperature result in degradation of the power delivered by the solar cells. Moreover, deposition of contaminants on the radiator could result in degradation of the optical properties of the radiating surface and the need for larger radiator to deliver the required amount of waste heat.

6.2 EPS Contamination Analyses

The engineering tool used in performing induced Contamination analysis is a computer code entitled MOLFLUX which was developed at NASA–Johnson Space Center. For return flux calculations, the code uses the BGK method which is an approximation to Boltzman transport equations, whereas for direct flux calculation, the code assumes the contamination emission from surfaces as Lambertian, and with the help of a geometrical code such as TRASYS which provide the surface to surface view factors, the direct flux can then be calculated from one surface to another. TRASYS use is not limited to the surface to surface view factors. The return flux calculation requires knowing the point in space to surface view factors which are also provided by TRASYS. The deposition is calculated from the total flux incident on a particular surface and from the sticking coefficient which is approximated from the difference in temperatures between the emitting and the receiving surfaces (Ref. 9).

Results of a contamination assessment using MOLFLUX code was performed on a space station configuration which resembles the MB–2 flight mode when the PV arrays are first deployed. Based on an outgassing rate of 1×10^{-12} g/cm^2–s, surface temperatures that are change in orbit, a feathered flight configuration and outgassing as the sole contamination source, deposition on the solar arrays is calculated and reported in Table 4. Since deposition from outgassing is only one contributor to degradation among others such as deposition from shuttle docking and SSF reboost, the total degradation due to deposition from the three sources is expected to be higher than only from outgassing. The degradation of performance of the arrays due to deposition level shown in Table 4 is about 0.45%. However, the degradation caused by deposition equal to the deposition requirement reported in SSP 30426 "SSF Induced Contamination Control Requirement Document" was calculated to be approximately 1.15% over 15 years. This degradation factor encompasses the degradation induced by the SSF outgassing only (Ref. 4).

Item	Surface Deposition (g/cm^2–year)		
	Direct Flux	Return Flux	Total
Solar Array	$1.17\ 10^{-8}$	$3.59\ 10^{-9}$	$1.53\ 10^{-8}$
PVM Radiator	$1.28\ 10^{-7}$	$1.26\ 10^{-8}$	$1.41\ 10^{-7}$

Table 4. Total Surface Deposition on EPS Sensitive Surfaces of MB–1

7. CONCLUDING REMARKS

In this paper, a summary of the environmental interactions of the EPS was given. It is worth mentioning that these environmental effects are taken into consideration in the EPS design. The aforementioned analyses are undergoing continual update due to the change in the SSF configuration and the changes in the environmental requirements. Moreover, new programs and analyses to investigate unresolved issues such as effects of plasma sputtering, arcing effects, and dielectric breakdown and their impact on material performance and survivability in the LEO environment are planned. The results from the aforementioned analyses and testing programs will be used for refining the definition of the environmental factors to be used in the design of the various EPS components.

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16. Abstract

The Space Station Freedom will be operating in the Low Earth Orbit (LEO) environment. Such operation results in different potential interactions with the Space Station systems including the Electric Power System (EPS). These potential interactions result in environmental effects which include neutral species effects such as atomic oxygen erosion, effects of micrometeoroid and orbital debris impacts, plasma effects, ionizing radiation effects, and induced contamination degradation effects. The purpose of this paper is to briefly describe the EPS design and its interactions with the LEO environment and to discuss the results of analyses and testing programs planned and performed thus fat to resolve the environmental concerns related to the EPS and its function in the LEO environment.

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